Decoherence-free quantum memory for photonic state using atomic ensembles

Feng Mei, Ya-Fei Yu,* and Zhi-Ming Zhang†

Laboratory of Photonic Information Technology, School for Information and Photoelectronic Science and Engineering, South China Normal University, Guangzhou 510006, PR China

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Large scale quantum information processing requires stable and long-lived quantum memories. Here, using atom-photon entanglement, we propose an experimentally feasible scheme to realize decoherence-free quantum memory with atomic ensembles, and show one of its applications, remote transfer of unknown quantum state, based on laser manipulation of atomic ensembles, photonic state operation through optical elements, and single-photon detection with moderate efficiency. The scheme, with inherent fault-tolerance to the practical noise and imperfections, allows one to retrieve the information in the memory for further quantum information processing within the reach of current technology.

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Quantum information science involves the storage, manipulation and communication of information encoded in quantum systems. In the future, an outstanding goal in quantum information science is the faithful mapping of quantum information between a stable quantum memory and a reliable quantum communication channel. The quantum memory is a key element of quantum repeaters [1] that allow for long-distance quantum communication over realistic noisy quantum channel, which is also necessary for scalable linear optics quantum computation put forward by Knill et al. [2]. Atomic systems are excellent quantum memories, because appropriate internal electronic states can coherently store qubits over very long timescales. Photons, on the other hand, are the natural platform for the distribution of quantum information between remote qubits, by considering their ability to transmit large distance with little perturbation [3]. Recently, various quantum memory schemes for storing photonic quantum states have been proposed, involving employing one atom or two atoms in a high-Q cavity [4], all optical approaches [5], and coupling the light into the atomic ensembles [6]. However, the above schemes have several disadvantages. It is hard to efficiently couple a photon with a atom in a high-fineness cavity, all optical approaches have large transmission loss. Given these drawbacks it is of interest to explore the alternatives.

In this paper, different from the quantum memory schemes using electromagnetically induced transparency (EIT) [6], we propose a scheme to achieve the decoherent-free quantum memory with atom ensembles and linear optics by quantum teleportation. By using the photonic qubits as the information carriers and the collective atomic qubits as the quantum memory, the information can be encoded into the remote decoherence-free subspaces (DFS) [7, 8] of quantum memory via teleportation of an arbitrarily prepared quantum state. Compared with the above proposals, our protocol has the following significant advances: (i) It is not necessary to employ a cavity which works in the strong coupling regime. Instead, sufficiently strong interaction is achieved due to the collective enhancement of the signal-to-noise ratio [9, 10, 11]. (ii) Different from all optical approaches, the fidelity of our atomic memory is insensitive to photon loss. The photon loss only influences the probability of success. (iii) We use two atomic ensembles to encode a single logic qubit, the information is stored in a decoherent-free subspace (DFS) which can protect quantum information against decoherence effectively. (iv) Raman transition technique provides a controllable and decoherence-insensitive way of coupling between light and atoms, so the information storing in the quantum memory can be retrieved with ease for further quantum information processing. (v) Finally, by introducing the photon an additional degree of freedom with spatial modes, we get complete Bell state measurement (BSM) and improve the preparation efficiency a lot.

Before describing the detailed model, first we summarize the basic ideas of the scheme, which consists of four steps shown in Fig. 1. (A) Firstly, the entanglement between atomic ensembles and Stokes photon is generated. (B) The spatial mode is employed as additional degree of freedom of photon to encode the information we want to imprint. (C) Next, complete Bell state measurement is performed on the polarization and spatial qubits of photon. (D) Via the BSM results, the information will be faithfully encoded into the decoherent-free subspace (DFS) of atomic ensembles.

Step (A) — Entanglement between atom ensembles and photon [12] is crucial to achieve this task. In more detail, the basic element is a cloud of N identical atoms with the relevant level structure shown in Fig. 1(a). The metastable lower states $|g\rangle$ and $|s\rangle$ can correspond to hyperfine or Zeeman sublevels of the ground state of alkali-metal atoms, which have an experimentally demonstrated long lifetimes [13, 14]. To achieve effectively enhanced coupling to light, the atom ensembles should be preferably placed with pencil-shape. Initially, all the

*Electronic address: yfyuks@hotmail.com
†Electronic address: zmzhang@scnu.edu.cn

atoms are prepared in the ground state $|g\rangle$. Shining a synchronized short, off-resonant pump pulse into the atomic ensemble $j\,(j = L$ or $R)$ induces Raman transitions into the state $|s\rangle$. The emission of single Stokes photon results in the state $S_j^+ \left|0_a\right\rangle_j$ of atomic ensembles, where the ensemble ground state $\left|0_a\right\rangle = \otimes_i \left|g\right\rangle_i$,the symmetric collective mode $S = \left(1/\sqrt{N_a}\right) \sum_i \left|g\right\rangle_i \left\langle s\right|$ [15]. By the selection rules and the conservation of angular momentum, the pump pulse and the Stokes photon have the left (L) and right (R) circular polarization. Assume that the interaction time is short, so, the mean number of the forward-scattered Stokes photon is much smaller than 1. We can define signal light mode bosonic operator a for the Stokes pulse with its vacuum state denoted by $|0_p\rangle$, where $a^+ \left|0_p\right\rangle = \left|R\right\rangle$. The symmetric collective mode S and the signal light mode a are correlated with each other, which means, if the atomic ensemble is excited to the symmetric collective mode S^+, the accompanying emission photon will go to the signal light mode a^+, and vice versa. The whole state of atomic ensemble and the Stokes photon can be written as

$$\left|\phi\right\rangle_j = \left|0_a 0_p\right\rangle_j + \sqrt{p_{cj}} S_j^+ a_j^+ \left|0_a 0_p\right\rangle_j + o(p_{cj}), \qquad (1)$$

where $p_{cj} = 4 g_c^2 N_j L_j / c \left|\Omega\right|^2 / \triangle^2 t_p$ is the small excitation probability of single spin flip in the ensemble j [15, 16]. Here g_c is atom-field coupling constant, N_j and L_j are the linear density and the length of the atomic ensemble j. The probability can be controlled by adjusting the light-atom interaction time and pulse duration t_p. $o(p_{cj})$ represents its more excitations whose probabilities are equal to or smaller than p_{cj}^2 [15]. We should note that the scattered photon goes to some other optical modes other the signal mode. However, when N is large, the independent spontaneous emissions distribute over all the atomic modes, whereas the contribution to the signal light mode will be small [10]. So the use of atomic ensembles will result in a large signal-to-noise ratio [9, 10, 11] and improve the efficiency of the scheme.

We can make $p_{cL} = p_{cR}$, the two emitted Stokes pulses are interfered on a polarized beam splitter (PBS) after transmitting a quarter wave plate (QWP) shown in Fig. 1(b). The PBS transmits only H and reflects V polarization component, the QWP transforms the circularly polarized photon into linearly polarized photon by the operator $P_H^+ = \left|H\right\rangle\left\langle R\right|$ and $P_V^+ = \left|V\right\rangle\left\langle L\right|$. The small fraction of the transmitted classical pulses can be easily filtered through the filters. For the Stokes pulse from the atomic ensemble R, a polarization rotator $\mathbf{R}$ is inserted after the QWP. The function of the rotator is defined by the operator $\widetilde{R} = \left|H\right\rangle\left\langle V\right| + \left|V\right\rangle\left\langle H\right|$. By selecting orthogonal polarization, conditional on a single-photon detector click [17], the whole state of the atomic ensembles and the Stokes photon evolves into a maximal entangled state

$$\left|\Psi\right\rangle_{ap} = \left(S_L^+ + S_R^+ \widetilde{R}\right) / \sqrt{2} \left|vac\right\rangle_{ap}. \qquad (2)$$

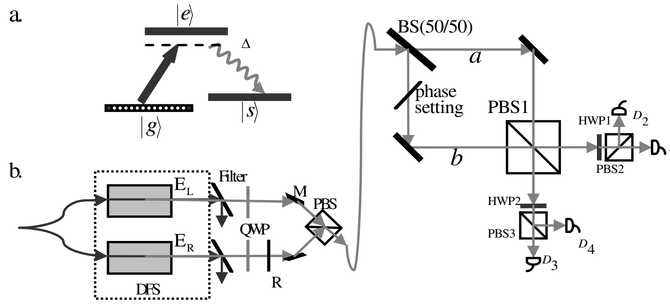

FIG. 1: Schematic setup for quantum memory scheme. (a) The relevant atomic level structure in the ensembles with $|e\rangle$ the excited state, $|g\rangle$ the ground state and $|s\rangle$ the metastable state for storing a qubit of information. The transition $|g\rangle \to |e\rangle$ can be coupled through the left circular classical pump pulse with the Rabi frequency Ω and a detuning $\triangle$, and the forward-scattered Stokes light comes from the transition $|e\rangle \to |s\rangle$, which has a right circular polarization. (b) The forward-scattered Stokes fields are collected after the filters which are polarization- and frequency- selective to filter the pumping light, and interfere at PBS. The output Stokes photon is coupled into a single-mode optical fiber and guided to the setup for preparing the information and subsequent polarization-spatial Bell-state measurement. The phase setting (α, β) allows to prepare any superposition of the spatial-mode qubit. Based on the PBSs and single-photon detectors, we can get the BSM in the polarization-spatial-mode Hilbert space of the Stokes photon.

Because during the Stokes photons from the ensemble L and R interfere in the input of the PBS, the information of their paths is erased. It denotes $\left|vac\right\rangle_{ap} \equiv \left|0_a\right\rangle_L \left|0_a\right\rangle_R \left|H\right\rangle$. Then, the entangled state can be rewritten as

$$\left|\Psi\right\rangle_{ap} = \left(\left|H\right\rangle\left|1\right\rangle_a + \left|V\right\rangle\left|0\right\rangle_a\right) / \sqrt{2}, \qquad (3)$$

where $\left|0\right\rangle_a = \left|0_a\right\rangle_L \left|1_a\right\rangle_R$, $\left|1\right\rangle_a = \left|1_a\right\rangle_L \left|0_a\right\rangle_R$ denote one spin flip in one of the ensembles. In fact, the generated entangled state will be mixed with a small vacuum component if we take into account the detector dark counts. However, the vacuum component is typically much smaller than the repetition frequency of the Raman pulses. Here, we can neglect this small vacuum component and the high order terms.

In the following, we will use the atomic ensembles qubit of the atom-photon entanglement as our quantum memory. Long-lived quantum memory is the keystone of quantum repeater. Unfortunately, due to environmental coupling, the stored information can be destroyed, so-called decoherence. Here, decoherence-free subspace (DFS) has been introduced to protect fragile quantum information against detrimental effects of decoherence. To establish the DFS, we utilize the state of a pair of atomic ensembles to encode a single logic qubit, i.e., $\left|0\right\rangle_a = \left|0_a\right\rangle_L \left|1_a\right\rangle_R$, $\left|1\right\rangle_a = \left|1_a\right\rangle_L \left|0_a\right\rangle_R$, so that the phase noise can be effectively suppressed.

Step (B) — After the generation of the entanglement, the emitted Stokes photon is coupled into a fiber and

guided to the setup illustrated in Fig. 1(b), where the state we want to imprint into the quantum memory is prepared. The Hilbert space of the photon is extended by using two spatial modes as an additional degree of freedom [18, 19]. The photon is coherently splitted into two spatial modes $|a\rangle$ and $|b\rangle$, remains in the state $|\varphi\rangle = \alpha|a\rangle + \beta|b\rangle$ by a polarization independent Mach-Zehnder interferometer. The phase setting (α, β) is determined by the optical path-length difference.

Step (C) — Critical to the third step of our scheme is the following identity:

$$\begin{aligned} |\varphi\rangle|\Psi\rangle_{ap} &= (\alpha|a\rangle + \beta|b\rangle) \otimes \left(|H\rangle|1\rangle_a + |V\rangle|0\rangle_a)/\sqrt{2}\right) \\ &= \frac{1}{2}(\left|\Psi^+\right\rangle|\widetilde{\varphi}\rangle + \left|\Psi^-\right\rangle\hat{\sigma}_z|\widetilde{\varphi}\rangle \\ &+ \left|\Phi^+\right\rangle\hat{\sigma}_x|\widetilde{\varphi}\rangle + \left|\Phi^-\right\rangle(i\hat{\sigma}_y)|\widetilde{\varphi}\rangle), \end{aligned} \tag{4}$$

where $|\Psi^\pm\rangle = (|H\rangle|b\rangle \pm |V\rangle|a\rangle)/\sqrt{2}$ and $|\Phi^\pm\rangle = (|H\rangle|a\rangle \pm |V\rangle|b\rangle)/\sqrt{2}$ denote the four polarization-spatial Bell states, $|\widetilde{\varphi}\rangle = \alpha|0\rangle_a + \beta|1\rangle_a$. We make a joint Bell state measurement on the polarization-spatial qubits. To achieve the BSM, the two spatial modes are combined in PBS1, and the polarization of photon will be analyzed in each output (see Fig. 1(b)). The half-wave plate (HWP) performs a Hardmard rotation $|H\rangle \to (|H\rangle + |V\rangle)/\sqrt{2}, |V\rangle \to (|H\rangle - |V\rangle)/\sqrt{2}$ on the polarization modes. If the detector D_1 has a click, then it denotes identification of one of the Bell state $|\Psi^+\rangle = (|H\rangle|b\rangle + |V\rangle|a\rangle)/\sqrt{2}$. Because after the combining of the two spatial modes on PBS1, the photonic orthogonal polarization can be coherently superposed into $(|H\rangle + |V\rangle)/\sqrt{2}$, which is rotated to H by HWP1 and then triggers the detector D_1. Accordingly, the click of the detector D_2, D_3 and D_4 corresponds to $|\Psi^-\rangle, |\Phi^+\rangle$ and $|\Phi^-\rangle$, respectively. After the BSM, i.e. the confirmation of only one click from the single photon detectors, the encoded information is transferred and encoded into the DFS of atomic ensembles.

Step (D) — According to the outcome of BSM, in the standard teleportation, a proper local Pauli unitary operation should be carried out on the atomic quantum memory to recover the original information. However, it is worth noticing the difficulty of laser manipulation to get the unitary operation of atomic ensembles. Thanks to the ease of performing precise unitary transformation on photon, we take the manner of marking instead of the recovering operation in the standard teleportation technique. The quantum memory can be made four different marks in a classic way, depending on the relevant BSM results. When there is a need to retrieve the information from the quantum memory, we can simultaneously shine a weak retrieval pulse with suitable frequency and polarization [20] into the atomic ensembles. The emitted anti-Stokes fields are then combined on PBS. As a result, the atomic qubit is converted back to single photon qubit. The efficiency of the transfer is close to unity at a single quantum level owing to the collective enhancement. Finally, we just apply corresponding unitary operation

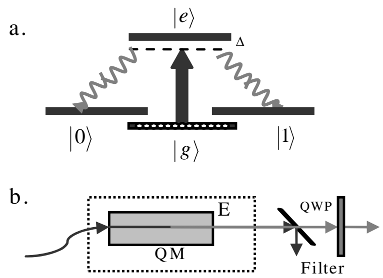

FIG. 2: (a) The relevant atomic level structure in the ensembles with $|g\rangle$ the ground state, $|e\rangle$ the excited state, and $|0\rangle$ and $|1\rangle$ the metastable state for storing a qubit of information. The transition $|g\rangle \to |e\rangle$ can be coupled through the classical laser pulse with the Rabi frequency $\Omega(t)$ and a detuning $\triangle$, and the forward-scattered Stokes photons come from the transition $|e\rangle \to |0\rangle$ and $|e\rangle \to |1\rangle$, which are left- and right-circularly polarized. (b) The forward-scattered Stokes photon is collected after the filter which is frequency selective to separate the pumping light, and transmits the quarter wave plate (QWP). Then the entanglement of atomic ensemble and photon is generated.

in agreement with the prior mark to recover the information. In fact, the information storing in the atomic ensembles is just the original one up to the local Pauli operation. The real formation (α, β) we stored has not been changed. The recovering operation is just suspended to facilitate the experimental realization within our technique.

On the other hand, the two atomic ensembles L and R can also be replaced by one ensemble, but with two metastable states $|0\rangle$ and $|1\rangle$ to store the quantum information shown in Fig. 2. The states $|g\rangle$, $|0\rangle$ and $|1\rangle$ correspond to the hyperfine or the Zeeman sublevels of alkali atoms in the ground-state manifold, and $|e\rangle$ corresponds to an excited state. The N atoms are initially prepared in the ground state $|G_a\rangle = \otimes_i |g\rangle_i$. The transition $|g\rangle \to |e\rangle$ is driven adiabatically by a weak classical laser pulse with the corresponding Rabi frequency denoted by $\Omega(t)$. With the short off-resonant driving pulse, only one atom is transferred nearly with unit probability to the excited state $|e\rangle$. The excited state will transit into the metastable states $|0\rangle$ or $|1\rangle$ with equal probabilities by emitting a left- or right-circularly polarized Stokes photon in the forward direction. Such emitting events are uniquely correlated with the excitation of the symmetric collective atomic mode S_h which is given by $S_h = \left(1/\sqrt{N_a}\right)\sum_i |g\rangle_i \langle h|$ $(h = 0, 1)$. The emission of single Stokes photon will result in the state of atomic ensembles by $|h\rangle_a = S_h^+ |0_a\rangle$.We also can define single mode bosonic operator a_h for the Stokes pulse with its vacuum state denoted by $|0\rangle_p$. The emitting process can be defined by $|L\rangle = a_0^+|0_p\rangle$ and $|R\rangle = a_1^+|0_p\rangle$, $|L\rangle$ and $|R\rangle$ denote the polarization of single Stokes photon. Before the emitted Stokes photon is coupled into the fiber, it transmits a quarter wave plate (QWP). By neglecting the small vacuum component and the high order terms,

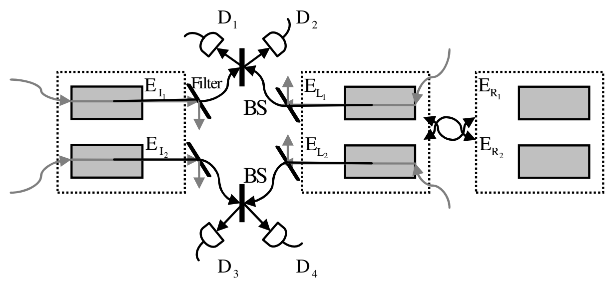

FIG. 3: Schematic setup for remote transfer of unknown quantum state. The unknown quantum state $(\alpha S_{I_2}^{+} + \beta S_{I_1}^{+}) \left|0_a 0_a\right\rangle_{I_1 I_2}$ is prepared in the atomic ensemble pair I. The atomic ensemble pair L and R are in a long-distance entangled state $\left|\Psi\right\rangle_{LR}$. After shined simultaneously by the repump pulse, the collective atomic excitations in the atomic ensemble I and L are transferred to the optical excitations, which are registered by the sigle-photon detectors.

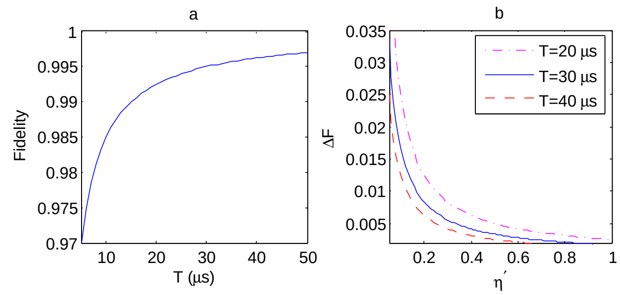

FIG. 4: (color online) (a) The improvement of quantum memory fidelity with the average preparation time. Here we choose the overall efficiency of photon detector, the optical appratus and fiber $\eta' = 1/3$. (b) The fidelity imperfection versus the overall efficiency η' with the average preparation time $T = 20$ μs, 30 μs, 40 μs.

the entangled state of the composite of atomic ensemble and photon can be written into the form

$$\left|\Psi\right\rangle_{ap} = \left(P_V^{+} S_0^{+} a_0^{+} + P_H^{+} S_1^{+} a_1^{+}\right)/\sqrt{2}\left|vac\right\rangle_{ap}, \qquad (5)$$

with $\left|vac\right\rangle_{ap} = \left|G_a\right\rangle\left|0_p\right\rangle$, i.e. $\left|\Psi\right\rangle_{ap} = (\left|H\right\rangle\left|1\right\rangle_a + \left|V\right\rangle\left|0\right\rangle_a)\sqrt{2}$. Via the above teleportation, the information will be stored into the atomic memory. Due to the collective enhanced coherent interaction, the atomic metastable states $\left|0\right\rangle_a$ and $\left|1\right\rangle_a$ can be transferred to optical excitations with high efficiency. So the information can be read out for further quantum information processing.

After the atomic quantum memory has been established, it is very necessary to consider its use in quantum communication protocols. Take remote transfer of unknown quantum state as an example. Suppose that a long-distance entangled state $\left|\Psi\right\rangle_{LR}$ between the double pairs of atomic ensembles L_1, L_2 and R_1, R_2 is generated by the quantum repeater [21, 22], $\left|\Psi\right\rangle_{LR} = (S_{L_1}^{+} S_{R_2}^{+} + S_{L_2}^{+} S_{R_1}^{+})/\sqrt{2}\left|vac\right\rangle_{LR}$, where $\left|vac\right\rangle_{LR} = \left|0_a 0_a 0_a 0_a\right\rangle_{L_1 L_2 R_1 R_2}$. We denote the entangled logical state by $\left|\Psi\right\rangle_{LR} = (\left|0\right\rangle_L \left|1\right\rangle_R + \left|1\right\rangle_L \left|0\right\rangle_R)/\sqrt{2}$, where $\left|0\right\rangle_{L(R)} = \left|0\right\rangle_{L_1(R_1)}\left|1\right\rangle_{L_2(R_2)}$, $\left|1\right\rangle_{L(R)} = \left|1\right\rangle_{L_1(R_1)}\left|0\right\rangle_{L_2(R_2)}$. The unknown quantum state storing in the two atomic ensembles I_1 and I_2 is $\left|\widetilde{\varphi}\right\rangle_I = (\alpha S_{I_2}^{+} + \beta S_{I_1}^{+})\left|0_a 0_a\right\rangle_{I_1 I_2} = \alpha\left|0\right\rangle_I + \beta\left|1\right\rangle_I$. Then shined simultaneously by the repump pulse which is near-resonant with the atomic transition $\left|s\right\rangle \rightarrow \left|e\right\rangle$, the collective atomic excitations in the ensembles I_1, L_1 and I_2, L_2 are transferred to the optical excitations, which, interfere respectively in a 50%-50% beam splitter, and are detected by two single-photon detectors on each output. If one click in D_1 or D_2, and one click in D_3 or D_4 have been confirmed, our protocol succeeds in transferring the unknown quantum state in the ensemble pair I into the ensemble pair R up to a local π-phase rotation. The fidelity of the remote transfer protocol is nearly perfect.

Finally, we briefly discuss the influence of practical noise and imperfections on the memory. The fidelity of the information we store in the atomic ensembles is mainly depend on the purity of entangled state. In practice, the entanglement between the atomic ensembles and the Stokes photon is in fact a mixed entangled state. The dominant noise arises from the channel attenuation, spontaneous photon scattering into random directions, coupling inefficiency for the channel, and inefficiency of single-photon detectors. Taking into account these noises, as will be shown below, the entangled state can be modified to

$$\rho_{ap} = p_0\left|vac\right\rangle_{ap}\left\langle vac\right| + p_1\left|\Psi\right\rangle_{ap}\left\langle\Psi\right| + p_o\rho_o, \qquad (6)$$

where p_0, p_1 and p_o are the probabilities of the vacuum state that the two atomic ensembles are in the ground state, one-excited state and the states with more excitations. Then we will give the probability an analysis. (i) We assume the probability of creating a Stokes photon behind PBS is $2p_c$, the detection efficiency η [23] is determined by the finite photon-collection (coupling) efficiency of the optical apparatus, χ, and by the quantum efficiency of the detector itself, i.e. the efficiency of distinguishing single photon click event from more photons, η_d, so the success probability of getting a single-photon detector click is determined as $p_1 \approx 2p_c\chi\eta_d e^{-L_0/L_{att}}$, where we have considered the channel attenuation factor as $e^{-L_0/L_{att}}$ [15], L_{att} is the channel attenuation length, and the other noise is independent of the communication length L_0. (ii) In the entanglement generation step, we have neglected the influence of the detector dark counts which is denoted by p_{dc} in each Raman round. In fact, it contributes to the vacuum component with the probability $p_0 \approx p_{dc}/(p_c\eta')$, $\eta' = \eta e^{-L_0/L_{att}}$ denotes the overall efficiency of the single-photon detector, the optical apparatus and channel in the scheme. Now, we take it into account. However, this vacuum component is typically very small since the normal dark count rate (100 Hz) is much smaller than the repetition frequency (10 MHz) of the

Raman pulses [15]. In addition, finally this component will be automatically eliminated in our scheme since its effect can be included by the detector inefficiency in the application measurements. (iii) If more than one atom is excited to the collective mode S, due to the inefficiency of the photon detector, there is only one click. The probability of this event is given by $p_o \sim p_c^n \chi(1-\eta_d)e^{-L_0/L_{att}}$ (decays exponentially with the number of excited atoms n). So, the fidelity between the generated state (6) and the ideal state (3) is decreased by the high-order component which is proportional to p_c, we can simply estimate the fidelity imperfection of our quantum memory $\Delta F = 1 - F \approx p_c$. Decreasing the small controllable excitation probability p_c for each driving Raman pulse, we can make the fidelity of the information close to one, but the longer preparation time T is cost. We have to repeat the process about $1/p_1$ times, with the total average preparation time $T \sim 1/(p_1 f_p)$, where f_p is the repetition frequency of the Raman pulses. As evident from Fig. 4(a), the fidelity of quantum memory can exceed 0.99 for the average preparation time $T > 15$ μs. Furthermore, the fidelity is insensitive to the variation of the overall efficiency η' caused by the single-photon detector, the optical apparatus and channel shown in Fig. 4(b). For instance, the change of the fidelity is about 10^{-2} for η' varying from 0.1 to 1. The Fig. 4(b) also shows that the fidelity is more insensitive to the overall efficiency η' with the increase of the average preparation time.

In summary, resorting to the idea of quantum teleportation, we have proposed a quantum memory scheme to imprint the quantum state of the photon into the DFS of atomic ensembles with high fidelity, and show one of applications with the memory. Moreover, based on the current technology of laser manipulation, photonic state operation through optical elements, and single-photon detection with moderate efficiency, the scheme is inherently resilient to the noise. Due to the long coherent time of atomic ensemble [13, 14], the teleported information can finally be read out for further quantum information applications.

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Decoherence-free quantum memory for photonic state using atomic ensembles

Feng Mei, Ya-Fei Yu,* and Zhi-Ming Zhang†
Laboratory of Photonic Information Technology, School for Information and Photoelectronic Science and Engineering, South China Normal University, Guangzhou 510006, PR China
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Large scale quantum information processing requires stable and long-lived quantum memories. Here, using atom-photon entanglement, we propose an experimentally feasible scheme to realize decoherence-free quantum memory with atomic ensembles, and show one of its applications, remote transfer of unknown quantum state, based on laser manipulation of atomic ensembles, photonic state operation through optical elements, and single-photon detection with moderate efficiency. The scheme, with inherent fault-tolerance to the practical noise and imperfections, allows one to retrieve the information in the memory for further quantum information processing within the reach of current technology.

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Quantum information science involves the storage, manipulation and communication of information encoded in quantum systems. In the future, an outstanding goal in quantum information science is the faithful mapping of quantum information between a stable quantum memory and a reliable quantum communication channel. The quantum memory is an essential ingredient of quantum repeaters [?] that allow for long-distance quantum communication over realistic noisy quantum channels and it is also necessary for scalable all-optical quantum computation as proposed by Knill et al. [?]. Atomic systems are excellent quantum memories, because appropriate internal electronic states can coherently store qubits over very long timescales. Photons, on the other hand, are the natural platform for the distribution of quantum information between remote qubits, by considering their ability to transmit large distance with little perturbation. Recently, various quantum memory schemes for storing photonic quantum states have been proposed, such as the use of a single atom in a high-Q cavity [?], all optical approaches [?], and storing photons in atomic ensembles [?]. However, the above schemes have several drawbacks. It is hard to efficiently couple a photon with a atom in a high-fineness cavity, all optical approaches have significant photon loss at switches. Given these disadvantages it is of interest to explore the alternatives.

In this paper, different from the quantum memory schemes using electromagnetically induced transparency (EIT) [?], we propose a scheme to achieve the decoherent-free quantum memory with atom ensembles and linear optics by quantum teleportation. By using the photonic qubits as the information carriers and the collective atomic qubits as the quantum memory, the information can be encoded into the remote decoherence-free subspaces (DFS) [? ?] of quantum memory via teleportation of an arbitrarily prepared quantum state. Compared with the above proposals, our protocol has the following significant advances: (i) It is not necessary to employ a cavity which works in the strong coupling regime. Instead, sufficiently strong interaction is achieved due to the collective enhancement of the signal-to-noise ratio [? ? ?]. (ii) Different from all optical approaches, the fidelity of our atomic memory is insensitive to photon loss. The photon loss only influences the probability of success. In fact, within the current technology, an overall transmission attenuation of 10^{-4} is tolerable [?]. (iii) We use two atomic ensembles to encode a single logic qubit, the information is stored in a decoherent-free subspace (DFS) which can protect quantum information against decoherence effectively. (iv) Raman transition technique provides a controllable and decoherence-insensitive way of coupling between light and atoms, so the information storing in the quantum memory can be retrieved with ease for further quantum information processing. (v) Finally, by introducing the photon an additional degree of freedom with spatial modes, we get complete Bell state measurement (BSM) and improve the preparation efficiency a lot.

Before describing the detailed model, first we summarize the basic ideas of the scheme, which consists of four steps shown in Fig. 1. (A) Firstly, the entanglement between atomic ensembles and Stokes photon is generated. (B) The spatial mode is employed as additional degree of freedom of photon to encode the information we want to imprint. (C) Next, complete Bell state measurement is performed on the polarization and spatial qubits of photon. (D) Via the BSM results, the information will be faithfully encoded into the decoherent-free subspace (DFS) of atomic ensembles.

Step (A) — Entanglement between atom ensembles and photon [?] is crucial to achieve this task. In more detail, the basic element is a cloud of N identical atoms with the relevant level structure shown in Fig. 1(a). The metastable lower states $|g\rangle$ and $|s\rangle$ can correspond to hyperfine or Zeeman sublevels of the ground state of alkali-metal atoms, which have an experimentally demonstrated long lifetimes [? ?]. To achieve ef-

*Electronic address: yfyuks@hotmail.com
†Electronic address: zmzhang@scnu.edu.cn

fectively enhanced coupling to light, the atom ensembles should be preferably placed with pencil-shape. Initially, all the atoms are prepared in the ground state $|g\rangle$. Shining a synchronized short, off-resonant pump pulse into the atomic ensemble j ($j = L$ or R) induces Raman transitions into the state $|s\rangle$. The emission of single Stokes photon results in the state $S_j^+ |0_a\rangle_j$ of atomic ensembles, where the ensemble ground state $|0_a\rangle = \otimes_i |g\rangle_i$,the symmetric collective mode $S = \left(1/\sqrt{N_a}\right) \sum_i |g\rangle_i \langle s|$ [**?**]. By the selection rules and the conservation of angular momentum, the pump pulse and the Stokes photon have the left (L) and right (R) circular polarization. Assume that the interaction time is short, so, the mean number of the forward-scattered Stokes photon is much smaller than 1. We can define signal light mode bosonic operator a for the Stokes pulse with its vacuum state denoted by $|0_p\rangle$, where $a^+ |0_p\rangle = |R\rangle$. The symmetric collective mode S and the signal light mode a are correlated with each other, which means, if the atomic ensemble is excited to the symmetric collective mode S^+, the accompanying emission photon will go to the signal light mode a^+, and vice versa. The whole state of atomic ensemble and the Stokes photon can be written as

$$|\phi\rangle_j = |0_a 0_p\rangle_j + \sqrt{p_{cj}} S_j^+ a_j^+ |0_a 0_p\rangle_j + o(p_{cj}), \qquad (1)$$

where $p_{cj} = 4g_c^2 N_j L_j / c \, |\Omega|^2 / \triangle^2 t_p$ is the small excitation probability of single spin flip in the ensemble j [**? ?**]. Here g_c is atom-field coupling constant, N_j and L_j are the linear density and the length of the atomic ensemble j. The probability can be controlled by adjusting the light-atom interaction time and pulse duration t_p. $o(p_{cj})$ represents its more excitations whose probabilities are equal to or smaller than p_{cj}^2 [**?**]. We should note that the scattered photon goes to some other optical modes other the signal mode. However, when N is large, the independent spontaneous emissions distribute over all the atomic modes, whereas the contribution to the signal light mode will be small [**?**]. So the use of atomic ensembles will result in a large signal-to-noise ratio [**? ? ?**] and improve the efficiency of the scheme.

We can make $p_{cL} = p_{cR}$, the two emitted Stokes pulses are interfered on a polarized beam splitter (PBS) after transmitting a quarter wave plate (QWP) shown in Fig. 1(b). The PBS transmits only H and reflects V polarization component, the QWP transforms the circularly polarized photon into linearly polarized photon by the operator $P_H^+ = |H\rangle \langle R|$ and $P_V^+ = |V\rangle \langle L|$. The small fraction of the transmitted classical pulses can be easily filtered through the filters. For the Stokes pulse from the atomic ensemble R, a polarization rotator $\mathbf{R}$ is inserted after the QWP. The function of the rotator is defined by the operator $\widetilde{R} = |H\rangle \langle V| + |V\rangle \langle H|$. By selecting orthogonal polarization, conditional on a single-photon detector click [**?**], the whole state of the atomic ensembles and the Stokes photon evolves into a maximal entangled state

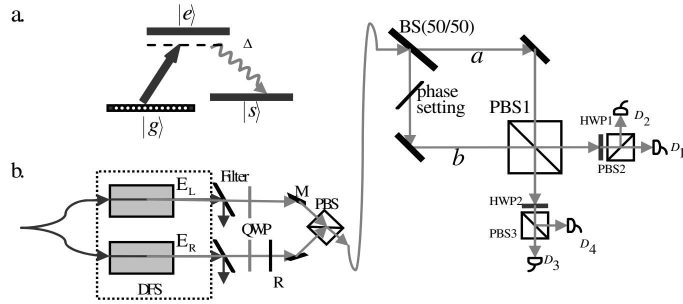

FIG. 1: Schematic setup for quantum memory scheme. (a) The relevant atomic level structure in the ensembles with $|e\rangle$ the excited state, $|g\rangle$ the ground state and $|s\rangle$ the metastable state for storing a qubit of information. The transition $|g\rangle \to |e\rangle$ can be coupled through the left circular classical pump pulse with the Rabi frequency Ω and a detuning $\triangle$, and the forward-scattered Stokes light comes from the transition $|e\rangle \to |s\rangle$, which has a right circular polarization. (b) The forward-scattered Stokes fields are collected after the filters which are polarization- and frequency- selective to filter the pumping light, and interfere at PBS. The output Stokes photon is coupled into a single-mode optical fiber and guided to the setup for preparing the information and subsequent polarization-spatial Bell-state measurement. The interferometric phase setting (α, β) allows to prepare any superposition of the spatial-mode qubit. Based on the PBSs and single-photon detectors, we can get the BSM in the polarization-spatial-mode Hilbert space of the Stokes photon.

$$|\Psi\rangle_{ap} = \left(S_L^+ + S_R^+ \widetilde{R}\right) / \sqrt{2} \, |vac\rangle_{ap} . \qquad (2)$$

Because during the Stokes photons from the ensemble L and R interfere in the input of the PBS, the information of their paths is erased. It denotes $|vac\rangle_{ap} \equiv |0_a\rangle_L |0_a\rangle_R |H\rangle$. Then, the entangled state can be rewritten as

$$|\Psi\rangle_{ap} = \left(|H\rangle |1\rangle_a + |V\rangle |0\rangle_a\right) / \sqrt{2}, \qquad (3)$$

where $|0\rangle_a = |0_a\rangle_L |1_a\rangle_R$, $|1\rangle_a = |1_a\rangle_L |0_a\rangle_R$ denote one spin flip in one of the ensembles. In fact, the generated entangled state will be mixed with a small vacuum component if we take into account the detector dark counts. However, the vacuum component is typically much smaller than the repetition frequency of the Raman pulses. Here, we can neglect this small vacuum component and the high order terms.

In the following, we will use the atomic ensembles qubit of the atom-photon entanglement as our quantum memory. Long-lived quantum memory is the keystone of quantum repeater. Unfortunately, due to environmental coupling, the stored information can be destroyed, so-called decoherence. Here, decoherence-free subspace (DFS) has been introduced to protect fragile quantum information against detrimental effects of decoherence. To establish the DFS, we utilize the state of a pair of

atomic ensembles to encode a single logic qubit, i.e., $|0\rangle_a = |0_a\rangle_L |1_a\rangle_R$, $|1\rangle_a = |1_a\rangle_L |0_a\rangle_R$, so that the phase noise can be effectively suppressed.

Step (B) — After the generation of the entanglement, the emitted Stokes photon is coupled into a fiber and guided to the setup illustrated in Fig. 1(b), where the state we want to imprint into the quantum memory is prepared. The Hilbert space of the photon is extended by using two spatial modes as an additional degree of freedom [**?** **?**]. The photon is coherently splitted into two spatial modes $|a\rangle$ and $|b\rangle$, remains in the state $|\varphi\rangle = \alpha |a\rangle + \beta |b\rangle$ by a polarization independent Mach-Zehnder interferometer. The phase setting (α, β) is determined by the optical path-length difference.

Step (C) — Critical to the third step of our scheme is the following identity:

$$\begin{aligned} |\varphi\rangle |\Psi\rangle_{ap} &= (\alpha |a\rangle + \beta |b\rangle) \otimes \left(|H\rangle |1\rangle_a + |V\rangle |0\rangle_a)/\sqrt{2} \right) \\ &= \frac{1}{2}(\left|\Psi^+\right\rangle |\widetilde{\varphi}\rangle + \left|\Psi^-\right\rangle \hat{\sigma}_z |\widetilde{\varphi}\rangle \\ &+ \left|\Phi^+\right\rangle \hat{\sigma}_x |\widetilde{\varphi}\rangle + \left|\Phi^-\right\rangle (i\hat{\sigma}_y) |\widetilde{\varphi}\rangle), \end{aligned} \tag{4}$$

where $|\Psi^\pm\rangle = (|H\rangle |b\rangle \pm |V\rangle |a\rangle)/\sqrt{2}$ and $|\Phi^\pm\rangle = (|H\rangle |a\rangle \pm |V\rangle |b\rangle)/\sqrt{2}$ denote the four polarization-spatial Bell states, $|\widetilde{\varphi}\rangle = \alpha |0\rangle_a + \beta |1\rangle_a$. We make a joint Bell state measurement on the polarization-spatial qubits. To achieve the BSM, the two spatial modes are combined in PBS1, and the polarization of photon will be analyzed in each output (see Fig. 1(b)). The half-wave plate (HWP) performs a Hardmard rotation $|H\rangle \to (|H\rangle + |V\rangle)/\sqrt{2}, |V\rangle \to (|H\rangle - |V\rangle)/\sqrt{2}$ on the polarization modes. If the detector D_1 has a click, then it denotes identification of one of the Bell state $|\Psi^+\rangle = (|H\rangle |b\rangle + |V\rangle |a\rangle)/\sqrt{2}$. Because after the combining of the two spatial modes on PBS1, the photonic orthogonal polarization can be coherently superposed into $(|H\rangle + |V\rangle)/\sqrt{2}$, which is rotated to H by HWP1 and then triggers the detector D_1. Accordingly, the click of the detector D_2, D_3 and D_4 corresponds to $|\Psi^-\rangle, |\Phi^+\rangle$ and $|\Phi^-\rangle$, respectively. After the BSM, i.e. the confirmation of only one click from the single photon detectors, the encoded information is transferred and encoded into the DFS of atomic ensembles.

Step (D) — According to the outcome of BSM, in the standard teleportation, a proper local Pauli unitary operation should be carried out on the atomic quantum memory to recover the original information. However, it is worth noticing the difficulty of laser manipulation to get the unitary operation of atomic ensembles. Thanks to the ease of performing precise unitary transformation on photon, we take the manner of marking instead of the recovering operation in the standard teleportation technique. The quantum memory can be made four different marks in a classic way, depending on the relevant BSM results. When there is a need to retrieve the information from the quantum memory, we can simultaneously shine a weak retrieval pulse with suitable frequency and polarization [**?**] into the atomic ensembles. The emitted anti-Stokes fields are then combined on PBS. As a result, the atomic qubit is converted back to single photon qubit. The efficiency of the transfer is close to unity at a single quantum level owing to the collective enhancement. Finally, we just apply corresponding unitary operation in agreement with the prior mark to recover the information. In fact, the information storing in the atomic ensembles is just the original one up to the local Pauli operation. The real formation (α, β) we stored has not been changed. The recovering operation is just suspended to facilitate the experimental realization within our technique.

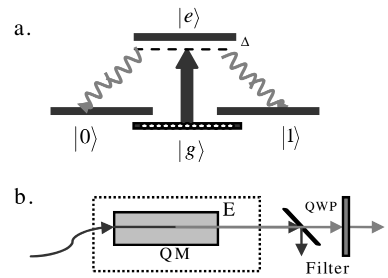

FIG. 2: (a) The relevant atomic level structure in the ensembles with $|g\rangle$ the ground state, $|e\rangle$ the excited state, and $|0\rangle$ and $|1\rangle$ the metastable state for storing a qubit of information. The transition $|g\rangle \to |e\rangle$ can be coupled through the classical laser pulse with the Rabi frequency $\Omega(t)$ and a detuning $\triangle$, and the forward-scattered Stokes photons come from the transition $|e\rangle \to |0\rangle$ and $|e\rangle \to |1\rangle$, which are left- and right-circularly polarized. (b) The forward-scattered Stokes photon is collected after the filter which is frequency selective to separate the pumping light, and transmits the quarter wave plate (QWP). Then the entanglement of atomic ensemble and photon is generated.

On the other hand, the two atomic ensembles L and R can also be replaced by one ensemble, but with two metastable states $|0\rangle$ and $|1\rangle$ to store the quantum information shown in Fig. 2. The states $|g\rangle$, $|0\rangle$ and $|1\rangle$ correspond to the hyperfine or the Zeeman sublevels of alkali atoms in the ground-state manifold, and $|e\rangle$ corresponds to an excited state. The N atoms are initially prepared in the ground state $|G_a\rangle = \otimes_i |g\rangle_i$. The transition $|g\rangle \to |e\rangle$ is driven adiabatically by a weak classical laser pulse with the corresponding Rabi frequency denoted by $\Omega(t)$. With the short off-resonant driving pulse, only one atom is transferred nearly with unit probability to the excited state $|e\rangle$. The excited state will transit into the metastable states $|0\rangle$ or $|1\rangle$ with equal probabilities by emitting a left- or right-circularly polarized Stokes photon in the forward direction. Such emitting events are uniquely correlated with the excitation of the symmetric collective atomic mode S_h which is given by $S_h = \left(1/\sqrt{N_a}\right) \sum_i |g\rangle_i \langle h|$ $(h = 0, 1)$. The emission of single Stokes photon will result in the state of atomic ensembles by $|h\rangle_a = S_h^+ |0_a\rangle$ .We also can define single mode bosonic operator a_h for the Stokes pulse with its vacuum state denoted by $|0\rangle_p$. The emitting process can